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An assessment of collective action drivers of carbon storage in Nepalese forest commons

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ABSTRACT

Decentralized forestry has evolved as a strategy for the management of forests in many developing countries and key institutional factors driving forest collective action have also been identified. We analyzed 130 Nepalese forest commons to determine how key forest collective action variables are associated with carbon storage. As expected, we find household participation in forest management and public audit have favorable implications for carbon storage. However, we also find conservation duration, communities' ability to modify rules and existence of penalty system have constraining, and mutual trust have no or neutral implications for carbon storage. These findings indicate that better collective action does not necessarily store additional carbon. If forest commons in developing countries are to contribute to global climate change initiatives, such as the United Nation's program on Reducing Emissions from Deforestation and Forest Degradation (REDD +), our findings suggest the need for dedicated policies and programs to create additional incentives.

1. Introduction

Approximately 15.5% of global forests and 25% of developing country forests are under the control of local communities ("forest commons") and this trend is increasing (Rights and Resources Initiatives [RRI], 2014; Kumar, 2002). A key reason for this trend is that governments in many developing countries have been devolving and decentralizing forest control with the aim to stop deforestation, manage forests sustainably and increase provision of forest products to communities (Larson and Soto, 2008; Persha et al., 2011). Given their importance, forests controlled by communities are also potentially critical for contributing to climate change mitigation through carbon storage, particularly with the emergence of the United Nation's program on Reducing Emissions from Deforestation and Forest Degradation (REDD +) as a cost-effective strategy to reduce emissions (Kinderman et al., 2008). Karky and Skutsch (2010) estimates that the opportunity cost of carbon sequestration in community forests in Nepal may be less than $1.00 per ton, but more recent literature calls these very low Nepal estimates into question (Maraseni et al., 2014; Pandit et al., 2017).

Effective management of forest commons relies heavily on collective action, which depends on trust and reciprocity among community members, who adopt norms while pursuing contingent strategies in complex and uncertain environments (Ostrom, 1990). Norms are critical to resolving social dilemmas via building and maintaining community self-organization, trust and reciprocity. Ostrom (1990) identified norms guiding collective action, which she articulated in terms of institutional design principles that can vary significantly across contexts (Cox et al., 2010). Such norm guiding collective action has been evident in effective management of forest resources in developing countries. For example, in Nepal forest collective action has contributed to reducing deforestation and forest degradation and restoring degraded forests (Department of Forest Research and Survey [DFRS], 2015; Gautam et al., 2002), but communities' harvesting, grazing and burning in some cases have also resulted in loss of forest carbon (Flint and Richards, 1994; Food and Agriculture Organization [FAO], 1993; Goldammer, 1990).

Agrawal and Angelsen (2009) highlight the need to strengthen collective action that increases both carbon storage and livelihood outcomes. However, there remains large uncertainty whether and when forest commons sequester more carbon (Chazdon, 2008; Ranganathan et al., 2008; Beyene et al., 2015), making it difficult to know to what extent programs such as REDD + need to provide specific and direct incentives for carbon sequestration.

Using worldwide forest data and highly aggregated forest collective action elements, Chhatre and Agrawal (2009) demonstrate there are possibilities for both tradeoffs and synergies between carbon sequestration and livelihoods of communities. They conclude by suggesting the need for detailed studies to better understand the implications of REDD + when forests are controlled by communities. Similarly, in the Amazon, Bottazoi et al. (2014) recommend that focusing

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simultaneously on the intersection of institutional, socio-economic and biophysical factors is needed to better understand the implications of REDD +. In addition, Beyene et al. (2015) evaluate the effect of local community forestry collective action on carbon sequestration in Ethiopia, but find minor effects. Yadav et al. (2003), Gautam et al. (2003) and others claim that CFs in Nepal can help reduce forest degradation, which could imply less carbon emissions that should be credited under REDD +.

Nepal has a long history of community-based indigenous, traditional forest management practice. Building on such management practice, it has developed and adopted different models of community-based forest management such as community forestry, leasehold forestry, and government-managed forestry. It is one of the pioneer countries in creating legally supported forest commons over the last 40 years. Approximately 42% of the population are formally organized in ~19,000 Community Forest User Groups (CFUGs), which are engaged in managing ~1.8 million hectares of forests (Department of Forest, 2015). The CFUGs are autonomous public bodies that can acquire, possess, transfer and manage forests (Ministry of Law and Justice [MoLJ], 1993).

Using multivariate regression analysis and data from a sample of 130 forest commons and 1300 households across Nepal, we examine the relationship between key collective action drivers and carbon storage, while controlling for the effects of major conditioning variables, such as location, topography, quality and quantity of forests and population structures. Specifically, we consider communities' forest conservation histories, governance practices, monitoring and sanctioning, and social capital, as they constitute critical common property design principles (Cox et al., 2010; Ostrom, 1990).

2. Methods

2.1. Sampling and data collection

From February to May 2013 we collected data from 130 forest commons, 65 formal community forests (CF) and 65 non-community forests or non-CFs (NCFs), distributed in 42 districts across different physiographic regions (Fig. 1). As CFs are owned and actively managed by local communities and NCFs are owned and loosely managed by the government, but traditionally used by local communities, these categories make up the major types of forest commons in Nepal (Fig. 1).

Our interest in this paper is not to compare the results across CFs and NCFs, but to instead identify relationships between carbon stock and key collective action drivers, with less emphasis on management. We randomly selected CFs from a nationwide random sample used to evaluate the impact of the Nepal Community Forestry Program by the Nepalese government in 2010–12 (MoFSC, 2013). In related work (e.g. Bluffstone et al., 2018) that required comparability between CF and NCF observations, we selected NCFs in consultation with district forest office members. Such forests were not next to CFs to avoid being used simultaneously by the same communities.

We estimated that a sample of 325 forest plots was required for our study in the CFs to provide a nationally representative sample for Above-Ground Tree and Sapling Carbon ("carbon") estimation. This sample size was calculated based on a pilot survey of 45 forest plots (nine CFs) across physiographic regions that captured the greatest possible variance in the plot-wise carbon and applying Eq. (1) for a 10% error and 95% confidence level (Saxena and Singh, 1987).

$$N = C_v^2 t^2 / E^2 \tag{1}$$

where,

N = Required number of sample plots;
C_v = Coefficient of variation, s/μ (s = standard deviation and μ = sample mean);
E = Standard error, s/√n (n = sample number);
t = Value of student-t distribution for (n − 1) degree of freedom and 95% confidence level.

We sample 3 to 7 plots in each of the 65 CFs. We determined the number of plots in a forest according to the quintile distribution of forest size. These quintiles are computed separately for the hills and the southern plain lands (Terai) as average size of forests in the Terai is substantially greater than the hills (Table 1). The 65 NCFs are government forests that are used by the local communities and are often open access. Using the same criteria and methods as for the CFs, we selected 295 NCF plots in the 65 forests.[1]

To collect data on trees and saplings in each plot, we randomly selected concentric circular plots with radiuses of 8.92 m and 5.64 m to, respectively, which are suitable for moderate to dense vegetation and have been widely used (MacDicken, 1997). We identified the species and measured height and diameter at breast height (DBH) of each tree and DBH of each sapling.

We also randomly selected 10 households from each CFUG to complete questionnaires used to collect socio-economic data. We tested the questionnaires in two CFUGs and six households for their appropriateness and finalized them before conducting the full survey. We selected, trained and deployed 25 field researchers having either forestry or social science backgrounds. We closely and constantly monitored data collectors and supported them to ensure effectiveness of data collection and quality of data.

2.2. Analytical framework: variables, hypotheses and model specifications

We use multivariate regression to assess the relationships between collective action drivers and carbon storage by constructing a two-stage model. First, we estimate the carbon for each forest. Second, we construct a regression model with carbon as the continuous dependent variable and collective action drivers as the explanatory variables. We include critical conditioning variables in our model to mitigate potential biases due to omitted variables.

2.2.1. Variable selection and hypotheses setting

We carefully selected dependent, explanatory and conditioning variables (Table 2). We transformed all tree and plot data to the forest level (e.g., Mg C ha^{-1}) by averaging, and all household data to the community level so as to match the level of data for further analysis.[2]

2.2.1.1. Dependent variable. Our dependent variable is aboveground live carbon (Mg C ha^{-1}). We use Eqs. (1) and (2) to estimate Above-Ground Biomass (AGB). These allometric equations were developed based on a large dataset of trees across different climatic conditions of global sites, in dry (< 1500 mm average annual rainfall) and moist (1500–4000 mm average annual rainfall) forests, respectively (Chave et al., 2005) and recommended for Nepal by the Nepalese Government (Ministry of Forest and Soil Conservation [MoFSC], 2010). Approximately 95% and 5% of our samples are in moist and dry forests, respectively.

$$\text{AGB (kg)} = 0.112^{*}(\rho^{*} D^2 H)^{0.916} \tag{1}$$

$$\text{AGB (kg)} = 0.0509^{*} \rho^{*} D^2 H \tag{2}$$

[1] 30 plots had to be dropped due to data collection problems.

[2] For carbon, we converted the size-wise plot estimates (for trees 250 m^2 plot and for saplings 100 m^2 plot) to per hectare by multiplying by appropriate factors (e.g., by 40 for trees plots and by 100 for sapling plot). Then per hectare carbon of tree and sapling were added to get the total carbon per hectare at the plot level. Then by taking an average of plot level carbon (Mg C ha^{-1}), we estimated the forest level carbon (Mg C ha^{-1}). Similarly, other data collected at the plot level were averaged to estimate forest level data (e.g., slope, altitude and NDVI). Other data collected at the household level were aggregated to the community level. As community is the decision-making level for collective action and forest management, analysis at the community level is appropriate.

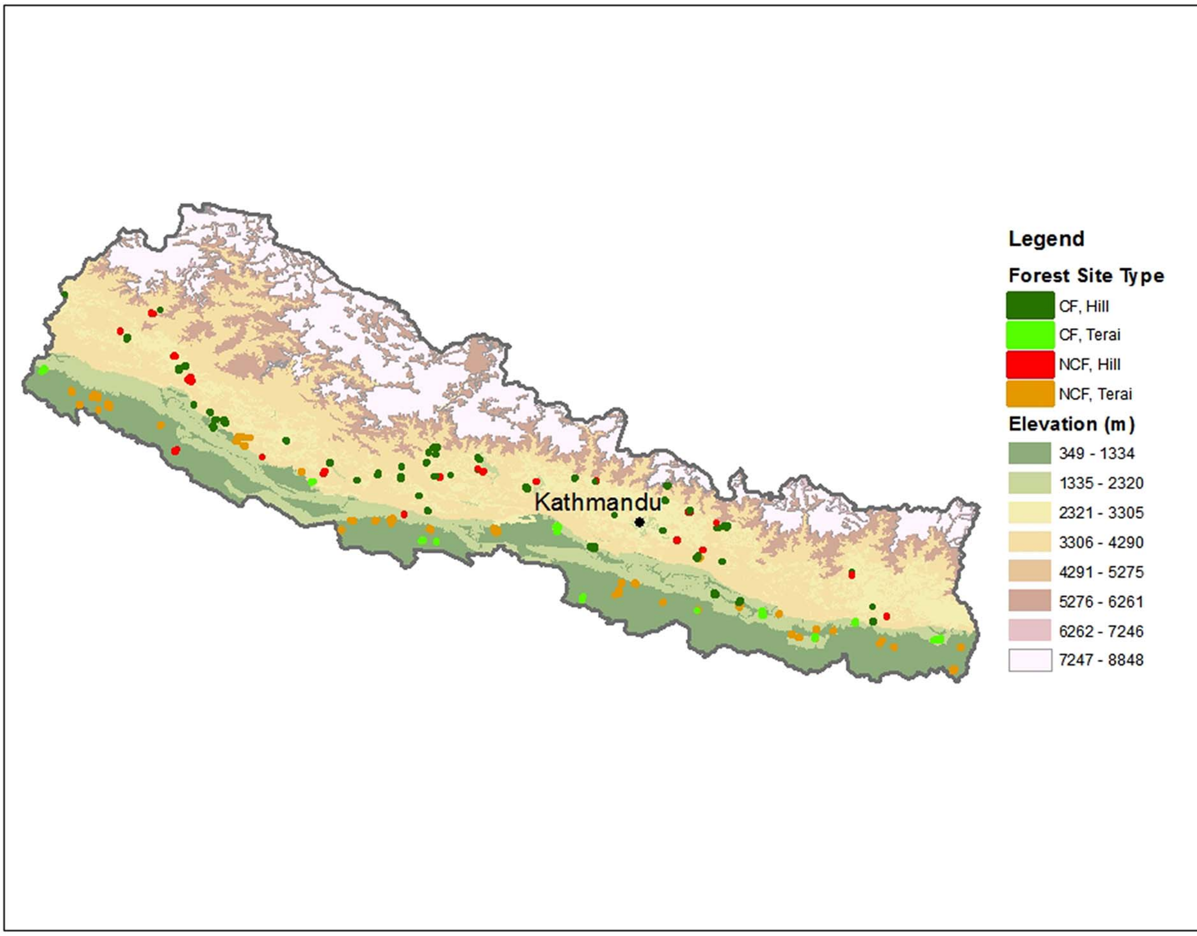

Fig. 1. Distribution of sample plots.

Table 1
Distribution of sample plots in CFs.

Quintile distribution	Forest size (ha)		Sample plots/forest	Number of forest	Number of plots
	Hill	Terai			
1st quintile	< 18	< 113	3	13	39
2nd quintile	18–64	113–154	4	13	52
3rd quintile	64–91	154–335	5	13	65
4th quintile	91–183	335–526	6	13	78
5th quintile	≥ 183	≥ 526	7	13	91

where,

ρ = Specific gravity of wood (g cm^{-3});
D = DBH;
H = Tree height

We use species-based wood specific gravity (Jackson, 1994) to calculate biomass. Where such information is not available, we use a general value derived from average specific gravity of associated species (same genus and family) by forest type (Baker et al., 2004; Ngugi et al., 2011). For saplings, we use Nepal-specific biomass equations developed by Tamrakar (2000) to estimate the green biomass, which was converted into dry biomass by multiplying by species fractions or the average of the associated species as identified in the literature. We use the fractions 0.627, 0.613, 0.58, 0.57, 0.545, 0.517, 0.5 and 0.45 for *Quercus* species, *Lyonia ovalifolia*, *Pinus roxburghii*, *Alnus nepalensis*, *Schima wallichii*, *Shorea robusta*, *Terminalia tomentosa* and *Pinus wallichiana,* respectively (Shrestha et al., 2006; Wihersaari, 2005; Bhatt and Tomar, 2002; Kataki and Konwer, 2002; Jain and Singh, 1999). For unidentified species, or where wood density information was not available for the species, genus or family, we use the mean wood density obtained from the database of species compiled for this study (e.g. Baker et al., 2004). We converted AGB into carbon stock by multiplying by 0.50 (IPCC, 2006).

2.2.1.2. *Explanatory variables*. We use six critical collective action drivers that reflect a community's (i) forest conservation history, (ii) participation in active forest management, (iii) ability to modify rules, (iv) ability to enforce sanctions, (v) social capital and (vi) transparency of forestry affairs. These drivers reflect common property institutional design principles (Ostrom, 1990) and are hypothesized to explain variation in forest management outcomes (Andersson and Gibson, 2007; Gibson et al., 2005; Agrawal and Ostrom, 2001).

On the premise that better collective action leads to the development of appropriate, productive forest-management plans and greater carbon storage, we hypothesize that our explanatory variables are positively associated with carbon storage. More years of conservation result in larger-sized trees and more carbon storage (Luyssaert et al., 2008) and carbon storage in mid-hill *Shorea robusta* forest has been found to increase at the rate of 2.6 Mg ha^{-1} yr^{-1} (Thapa-Magar and Shrestha, 2015). Participation of more people embraces a wide variety of traditional ecological knowledge that helps enhance the productivity of forests (Posey, 2008) and therefore more participation is expected to yield more carbon.

The ability of forest-managing communities to modify forest management rules and practices may have positive implications for forest quality, as communities can effectively use their traditional ecological

Table 2
Descriptions of dependent, explanatory and conditioning variables and their units (n = 130).

Notation	Variables (level at which data were collected[a])	Measurement unit	Mean (or proportion/ percent)[b]	Std. Dev.	Minimum	Maximum
A. Dependent variable						
Carbon	Average estimated carbon per hectare of a forest (forest plot)	Metric ton per hectare	92.53	76.06	0.1685	362.09
B. Explanatory variables[*]						
Conservation duration	Number of years households in a community have been engaged in the conservation of forest (community)	Number of years	13.63	4.98	1	23
Participating households	Proportion of households in a community that participate in forest management activities (household)	Proportion	0.74			
Rules modification	Community members can modify the rules of forest management and benefit sharing as per their interest (community)	Proportion	0.87			
Penalty system	Forest-managing community has a system of punishment for forest offenders (household)	Proportion	0.91			
Public audit	Existence of public audit practice in the forest-managing community (community)	Proportion	0.37			
Mutual trust	Existence of mutual trust among forest-managing community members (household)	Ordinal scale = Yes = 2, Neutral = 1, No = 0	1.65[c]	0.46[c]	0.1[c]	2[c]
C. Conditioning variables						
Terai	The forest is located geographically in the Terai (forest)	Proportion	0.56			
Forest area	The total area of a forest (forest)	Hectare	129.05	161.72	1.1	1088
NDVI 1989	NDVI was calculated for the month of November 1989 (forest plot)	Index	0.4253	0.0887	0.1216	0.5775
Indigenous population	Proportion of indigenous peoples and ethnic groups[d] in a forest-managing community (household)	Proportion	0.40			
Group households	The total number of households in a forest-managing community (community)	Number	295.82	588.09	12	6081
Elevation	The average elevation of a forest (forest plot)	Meter	774.14	633.38	75	2410.6
Slope	The average slope of a forest (forest plot)	Degree	15.79	12.63	0	46.25
Road distance	Time required for two-way travel to the nearest road (community)	1 ≤ 2 h, 2 = 2 h - < half-day, 3 = half-day, 4 ≥ half-day	1 = 72% 2 = 19% 3 = 4% 4 = 5%			

[*] As being part of a CF is highly correlated with a number of explanatory variables, we do not include CF fixed effects in the model.
[a] Data source (community questionnaire, household questionnaire or forest plot measurements) noted in parentheses.
[b] Mean is presented in case of ratio data and the data that were measured at household level and aggregated at community level. Percent is presented in case of nominal data measured at community level such as road distance.
[c] We measured mutual trust at the household level and aggregated (averaged) at the community level. These data represent such community level statistics.
[d] Nepal's Act that establish the Foundation for Development of Indigenous Nationalities, (2002) defines "indigenous nationalities…[as] those ethnic groups or communities, who have their own mother tongue and traditional customs, different cultural identity, distinct social structure and written or oral history".

knowledge even during times of unanticipated change (Turner et al., 2003; Berkes and Folke, 1994). Rule enforcement, including graduated sanctions, is a necessary condition for effective forest management (Gibson et al., 2005) and is therefore expected to lead to regeneration, less degradation and more carbon (Chhatre and Agrawal, 2008).

It is intuitive that mutual trust and transparency among the community members reduces conflicts and thereby may improve forest governance and management outcomes. Realizing this, the Nepalese government has been promoting community level public audits to increase transparency in decisions, activities (e.g., forest management, income generation, livelihood support, and community development), and financial transactions of forest-managing communities (MoFSC, 2008).

A number of other collective action variables exist, but are not included, because they are highly correlated with the above variables. For instance, communities' ability to change rules is positively correlated with community monitoring practices ($\rho = 0.37$, $p = 0.000$), equity in benefit sharing ($\rho = 0.58$, $p = 0.000$) and clarity in rules ($\rho = 0.46$, $p = 0.000$). Similarly, the proportion of households engaged in forest management is associated with the existence of a forest management plans ($\rho = 0.28$, $p = 0.002$); and mutual trust among households is negatively correlated with conflict in the community ($\rho = -0.29$, $p = 0.001$).

2.2.1.3. Conditioning variables. We control for eight conditioning variables that have frequently been cited in the literature as influencing forest carbon (e.g. see Beyene et al., 2015; Andersson and Agrawal, 2011; Chaiyo et al., 2011; Chhatre and Agrawal, 2009). These conditioning variables include the ecological region (e.g., Terai vs. Hills, see Fig. 1), forest area, baseline environmental quality proxied by the 1989 Normalized Difference Vegetation Index (NDVI),[3] community attributes (e.g., total number of households and proportion of indigenous population), time taken to travel to and from the road to the community (a proxy of market pressure), and topographic features (e.g., elevation and slope). The 1989 NDVI allows us to adjust for the vegetation level almost 25 years before the data were collected. We view including this variable as critical, because omitting historical environmental quality could lead to significant potential for bias.

Terai forests are dominated by a commercially valuable species, *Shorea robusta,* and accesses to roads coupled with a high rate of internal migration are believed to contribute to deforestation and degradation. The area of forest may affect carbon storage, as it provides physical space for carbon sequestration and/or storage. It is intuitive that more forest area generally provides more space for carbon storage. Elevation and slope affect temperature, rainfall and nutrients, with large effects on tree size, densities, canopy cover, and species composition.

Time required for travelling from a community to the nearest road or district headquarter is a critical measure of remoteness that affects a community's transportation costs and market access and may be negatively associated with commercial harvesting, leading to greater carbon storage. Due to differences in geography and market access, collective action in remote communities may be different from those closer to roads or markets. Larger numbers of households in a community demand a greater quantity of forest products and therefore exert greater pressures on forest resources. Higher competition in accessing forest products may make collective action more challenging and thereby affect forest condition. Indigenous groups consume more fuelwood than the average community due to their socio-cultural practices and economic strategies (Pokharel, 2003). Indigenous communities have their own systems of forest management locally suitable to their culture and practice most of which have led to sustainable management of forest resources (Baral, 2015).

2.2.2. Identification and model specification

Collective actions are related to common property rights, which are potentially endogenous institutional processes (Heltberg, 2001). Such endogeneity could generate biased estimates if reverse causality is present. For example, we would have biased estimates if groups choose to become CFs because their forests are endowed with more carbon. A second potential identification issue is the presence of unobserved confounders that simultaneously affect communities' decisions to opt into forest user groups, such as CFs, and carbon stocks.

Though we cannot rule out such problems, because our data are cross-sectional, there are important reasons such concerns may be overblown. First, as Hyde et al. (1996) note, communities have no or little incentive to invest in better collective action when forest resources are abundant; if there is no need to invest in collective action, why do it? Second, forest management behaviors are affected by multi-generational evolutions of socio-cultural, economic, environmental and livelihood values, knowledge and practices (Barth, 2008; Posey, 2008; Rappaport, 2008; Alcorn, 1981) and this is true in Nepal (Gautam, 1991). The current collective action behaviors of Nepalese communities and in similar rural contexts around the world (e.g. see Beyene et al., 2015) are therefore largely path-dependent.

Such behaviors are shaped based on collective action norms that existed well before 2013 when our data were collection. This observation implies that the contemporary collective action behaviors we observe are unlikely to be chosen by communities based on forest characteristics. Instead, selection into such norms is driven by the history of community cooperation and forest management that generally dates back generations. Though we do not claim that forest collective action is truly random, it is unlikely that there is significant selection bias.

We test the hypothesis that better forest quality has promoted collective action using our data. Table 3 presents the results of a probit regression of our forest quality metrics and collective action variables on CF status, which is a formal version of forest collective action. We find that forest quality and individual collective action behaviors (except public audit), which we examine in this paper, are unrelated to CF status (Table 3).

Indeed, in related work we find that CFs have less carbon than NCFs (Bluffstone et al., 2018; Luintel, 2016). The Nepalese government originally prioritized community forestry in degraded forests in hill region (Kanel and Shrestha, 2001; Kumar, 2002; Gilmour & Fisher, 1991), and maintained control of the best quality Terai forests that have high commercial value and revenue potential (Bhattarai, 2006; Gilmour & Fisher, 1991). This evidence strongly suggests that better forest quality did not drive more robust formal community forestry that is closely related to effective collective action in Nepal, and in any case we control for 1989 NDVI.

Though we cannot exclude the existence of confounders, in contexts like rural Nepal the presence of common exogenous factors that affect both collective action drivers and carbon storage is unlikely (Beyene et al., 2015). Effective collective action and forest commons management are difficult to initiate from the outside and instead typically emerge from complex local processes (Ostrom, 2009; Agrawal, 2007); indeed, collective action generally mitigates negative exogenous shocks (Agrawal and Yadama, 1997).

Furthermore, exogenous shocks affecting both forest commons and collective action drivers simultaneously are unlikely in Nepalese community forestry, because at least CFs, which we have shown to exhibit some of the collective action behaviors we are analyzing, are legally recognized as autonomous institutions with perpetual succession (MoLJ, 1995). Such a legal provision strengthens communities and

[3] In Nepal, NDVI fluctuates by moisture, with peak values immediately after the monsoon in early October and declining through winter, as water availability decreases (Krakauer et al., 2017). November could be a season of achieving an approximate average annual NDVI as it has moderate moisture and leaf fall has not occurred. Most importantly, satellite imagery in November is especially accurate due to clear skies and little rain throughout the country.

Table 3
Probit regression of forest quality and collective action variables on CF status.

Variables	Coefficient (*p*-value)
Conservation duration	0.0470 (0.101)
Participating household	− 0.6616 (0.372)
Rule change	1.1210 (0.979)
Penalty system	1.0950 (0.120)
Public audit	**0.9884 (0.002)**
Mutual trust	− 0.7148 (0.075)
Forest area	− 0.0002 (0.793)
NDVI1989	− 2.6970 (0.143)

Note: The bold coefficient (p-values) denotes that public audit is significantly related to CF status.

reduces the role of external factors. Because CFs operate according to five-year management plans, there is also substantial inertia in collective action; basically, there is little reason to believe that the behavior of CFs (though perhaps not non-CFs) is reactive to outside circumstances.

We first check Spearman correlations of the six explanatory variables with carbon storage. We also check the relationships among the independent variables to assess multicollinearity. We then assess the effect of our explanatory variables on carbon storage using Eq. (3).

$$Y = \beta_0 + \beta_i(X_i) + \varepsilon \quad (3)$$

where

Y	Carbon stock (tons)
β_0	Value of the function when $X_i = 0$
B_i	Rate of change in carbon storage for unit change in respective explanatory variables
X_i	Explanatory and conditioning variables used in the model
i	1, 2, …, n
ε	Stochastic error assumed to follow a standard normal distribution with zero mean and variance normalized to one

We conduct diagnostic checks by looking at both residual plots and statistics. Both graphical display of residual versus fitted values and the Ramsay Regression Specification Error test ($p > 0.05$) indicate no possibility of residual non-linearity. The Q-Q plot showed the normal distribution of residuals except in the lower and higher ends. The standardized versus fitted values of residuals and the Breusch-Pagan test rule out the possibility of heteroscedasticity of residuals ($p > 0.05$). The Cook's Distance value of < 0.17 does not suggest than any observations exert strong influence on the results. The maximum value of Variance Inflation Factors (1.06–2.53) rejects the possibility of multicollinearity.

3. Results and discussion

Spearman correlations of explanatory and conditional variables with carbon storage are shown in Table 4. The practice of public audit, forests being in Terai, forest area, 1989 NDVI and the number of households in forest-managing communities are positively, but moderately correlated with carbon storage ($\rho = 0.25$ to 0.42). Conservation duration, elevation and slope of forest are weakly, negatively correlated with carbon storage ($\rho = -0.15$ to -0.25). The rest of the variables show no statistically significant relationship with carbon storage. Our main interest is in the collective action drivers, which are not associated with carbon.

Because we are unable to fully rule out sample selection and confounders, the results should be considered indicative and correlations rather than true causality. Model 1 in Table 5 includes only collective action drivers and represents indicative results, as the effects could be spurious. We therefore present six additional regression models, which

Table 4
Spearman correlations with carbon stock.

Variables	Correlation (p-values)
Conservation duration	− 0.15 (0.081)
Participating households	0.14 (0.122)
Rules modification	− 0.02 (0.842)
Penalty system	− 0.08 (0.338)
Public audit	**0.25 (0.004)**
Mutual trust	0.06 (0.474)
Terai	**0.27 (0.002)**
Forest area	**0.42 (0.000)**
NDVI 1989	**0.38 (0.000)**
Indigenous population	− 0.14 (0.103)
Households in user group	**0.37 (0.000)**
Distance to district headquarter	− 0.09 (0.330)
Elevation	**− 0.22 (0.011)**
Slope	**− 0.25 (0.004)**

Note: The bold coefficients (p-values) denotes that public audit, Terai, forest area, NDVI 1989, households in user group, elevation and slope are significantly associated with carbon stock.

include all collective action variables and different sets of conditioning variables. All models are statistically significant ($p < 0.0001$) and explain 12% to 35% of the variance in carbon storage.

We find that collective action measures had a variety of correlations with carbon storage, adjusting for key community and environmental variables as in Model 7. We emphasize, as was done in Bluffstone et al. (2018), that carbon storage is not necessarily consistent with other important measures of forest quality. We particularly highlight the importance of adjusting for baseline environmental quality using the 1989 NDVI. The proportion of households engaged in the management of forest commons was not significant in Models 1, 2 and 3, but consistently and positively correlated with carbon storage in Models 4 to 7 once we include the 1989 NDVI. These models indicate an increase in each percent of households participating in management increases carbon storage by 37.18 to 41.14 Mg C ha^{-1}.

Communities' ability to change rules did not have a significant effect on carbon storage controlling only for geographical location and forest area. However, when we controlled the NDVI 1989 and other variables (e.g. population, topographic and geographical variables), unexpectedly the effect became negative (i.e., reduction of 36.89 to 38.47 Mg C ha^{-1} when communities can modify collective action rules.

In contrast to our expectation, in all models the number of years communities have managed their forests (“Conservation duration”) was negatively correlated with carbon storage both in the absence or presence of conditioning variables. Our estimates of 2.22 to 3.63 Mg C ha^{-1} reduction with each year of increase in community engagement in forest conservation were significant ($p \leq 0.1$ to < 0.05). This result is in line with the finding of Andersson and Agrawal (2011) who also find a negative association between forest quality and the number of years communities engaged in forest conservation. As shown in Table 3, conservation duration is weakly and negatively correlated with CF status.

Also, as opposed to our hypothesis, the existence of penalty systems was consistently negatively correlated with carbon storage (except Model 2); the quantity of carbon is less (from 50.82 to 74.18 Mg C ha^{-1}) if a community adopted a penalty system. The reduction was lower when controlling for the effects of geographical location of forest and forest area. This negative association of penalty systems with carbon contradicts the findings of Chhatre and Agrawal (2008), who estimate a positive association between local enforcement and forest quality. Mutual trust among the households within a forest-managing community did not explain variation in carbon storage. This finding is consistent with and without conditioning variables and contradicts the finding of Gibson et al. (1999) and Alcorn and Victor (1998) who argued that different measures of social capital explain the

Table 5
OLS regression of carbon stock.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Conservation duration	**−3.63***** (1.13)	**−3.17**** (1.28)	**−2.97***** (1.19)	**−2.22*** (1.19)	**−2.43**** (1.17)	**−2.48**** (1.19)	**−2.48*** (1.27)
Proportion of households participating in forest management	41.26 (25.28)	37.79 (24.58)	37.63 (22.87)	**37.18*** (22.29)	**41.14*** (22.27)	**40.89*** (22.38)	**40.43*** (22.75)
Rules modification	−28.34 (25.50)	−19.03 (24.98)	−38.59 (23.65)	**−36.89** (23.06)	**−38.47*** (22.59)	**−38.20*** (22.71)	**−37.98** (22.89)
Penalty system	**−70.52**** (33.37)	−54.20 (32.90)	**−50.82** (30.62)	**−71.43**** (30.79)	**−74.18**** (30.21)	**−74.61**** (30.38)	**−74.30**** (30.63)
Public audit	**41.54***** (13.83)	**42.47***** (13.43)	**22.26*** (13.29)	21.33 (12.96)	18.69 (13.11)	19.15 (13.31)	19.63 (13.46)
Mutual trust	4.59 (15.43)	6.29 (15.00)	6.63 (13.96)	5. 97 (13.60)	9.92 (13.41)	10.38 (13.60)	10.26 (13.72)
Terai		**36.53***** (12.65)	17.52 (12.52)	9.85 (12.52	10.41 (12.27)	11.21 (12.75)	4.86 (19.76)
Forest area			**0.19***** (0.04)	**0.16***** (0.04)	**0.17***** (0.04)	**0. 17***** (0.04)	**0.17***** (0.04)
NDVI1990				**191.81***** (70.50)	**161.68**** (70.03)	**161.01**** (70.37)	**160.94**** (70.94)
Indigenous population					**−47.58**** (18.34)	**−48. 16**** (18.90)	**−48.42**** (19.07)
Households in user group					0.01 (0.01)	0.01 (0.01)	0.00 (0.01)
Distance to district headquarter						1.26 (5.24)	1.81 (5.63)
Elevation							−0.002 (0.02)
Slope							−0.26 (0.77)
Constant	**177.74***** (43.50)	**127.25 (12.65)**	**133.13***** (42.57)	67.45 (48.00)	**94.08*** (48.08)	**91.50*** (49.45)	**99.48*** (53.04)
Residual standard error	71.08	69.04	64.24	62.61	61.29	61.54	62.02
Adjusted R-squared	0.1268	0.1759	0.2866	0.3226	0.3506	0.3454	0.3352
F statistic	4.121	4.935	7.479	7.822	7.332	6.672	5.645
Degree of freedom	123	122	121	120	118	117	115
P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ramsey test (p-value)	0.34 (0.711)	0.62 (0.540)	0.22 (0.806)	0.42 (0.661)	0.27 (0.763)	0.25 (0.781)	0.17 (0.843)
Breusch-Pagan test (p-value)	4.71 (0.582)	6.90 (0.439)	9.07 (0.336)	10.06 (0.346)	12.29 (0.342)	13.21 (0.354)	16.07 (0.309)
Cook's D	0.00–0.13	0.00–0.12	0.00–0.14	0.00–0.17	0.00–0.13	0.00–0.12	0.00–0.11
VIF	1.07–1.18	1.07–1.81	1.09–1.81	1.15–1.82	1.06–1.89	1.12–1.90	1.12–3.25

Standard errors in parentheses. Results do not change when "distance from community to district headquarter" is replaced by "distance from community to roadhead."
Note: Bold coefficients denotes that the corresponding variables are significantly related with the carbon stock in the given model.
* 0.1.
** 0.05.
*** 0.01.

condition of local forests.

Seven of the eight conditioning variables (except number of households) had the expected signs and in some cases estimates were statistically significant. Each additional hectare of forest increased carbon storage by 0.17–0.19 Mg C ha^{-1}, likely reflecting decreased pressure per hectare. NDVI 1989 was also positive and significant, confirming the findings of other studies (e.g. Beyene et al., 2015) that baseline ecological conditions are critical explainers of biological potential and physical space for carbon storage. Our results also suggest that carbon storage is sensitive to the ethnicities of managing populations; each additional proportion of indigenous population decreases carbon by an estimated 47.16–47.58 Mg C ha^{-1}. The effects of two-way travel time to district headquarters, elevation, slope and number of households were not significantly different from zero.

The significant relationship of carbon storage with location in Terai, forest area, NDVI and proportion of indigenous population indicate that these variables likely capture important unobserved factors such as climate that could be associated with both carbon and collective actions. For instance, all CFs carry out public audits (MoFSC, 2008) and forestry officials closely monitor and ensure that the communities having bigger forests comply with the rule. This is evident from our data as public audit has a positive, significant correlation with forest area ($\rho = 0.27$, $p = 0.002$) and number of households in the community ($\rho = 0.29$, $p = 0.001$). As we are not interested in analyzing the effects of conditioning variables, we do not view this issue as a problem. However, we cannot rule out potential confounders affecting our conditioning variables.

4. Conclusion

Using a nationally representative sample of CFs matched with non-CFs and their corresponding forest user groups and households, we analyzed the relationships between key collective action drivers and carbon storage. Our study contributes to recent literature on the relationship between collective action and forest management outcomes, particularly carbon storage (e.g., Beyene et al., 2015; Chazdon, 2008; Chhatre and Agrawal, 2009; Persha et al., 2011).

We do not find robust effects of collective action on carbon and instead find different collective action variables have favorable, constraining or neutral implications for carbon storage. For instance, proportion of household participation in forest management activities and (in some models) the existence of public audits has a positive relationship with forest carbon. The number of years communities have conserved the forest, ability of communities to modify rules and the existence of penalty systems we find to be negatively related to stored carbon. Mutual trust, which is a proxy for social capital, is found to have no relationship with carbon storage.

In sum, we find that collective action as currently constructed in Nepalese forest commons does not offer a robust explanation for differing levels of carbon stocks. However, our results are indicative due to data limitations and for the reasons noted, and should therefore be considered preliminary. From a policy standpoint, our results suggest that if community-based forestry is to yield carbon benefits, explicit policies and programs are critical. In other words, the Nepalese government may need to pay more attention to steering collective action

toward enhancing carbon storage, perhaps with monetary payments (e.g. via REDD +) if its forests are to yield carbon sequestration benefits.

Our study does not identify specific causal mechanisms, which suggests the need for further research, incorporating other collective action drivers and controlling for possible biases. It also suggests the need to rethink and perhaps reorient collective action practices in Nepalese forest commons if it is appropriate that they contribute to global climate change initiatives, such as REDD +.

Declaration of conflicting interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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